Measurements and models of electric fields in the *in vivo* human brain during transcranial electric stimulation

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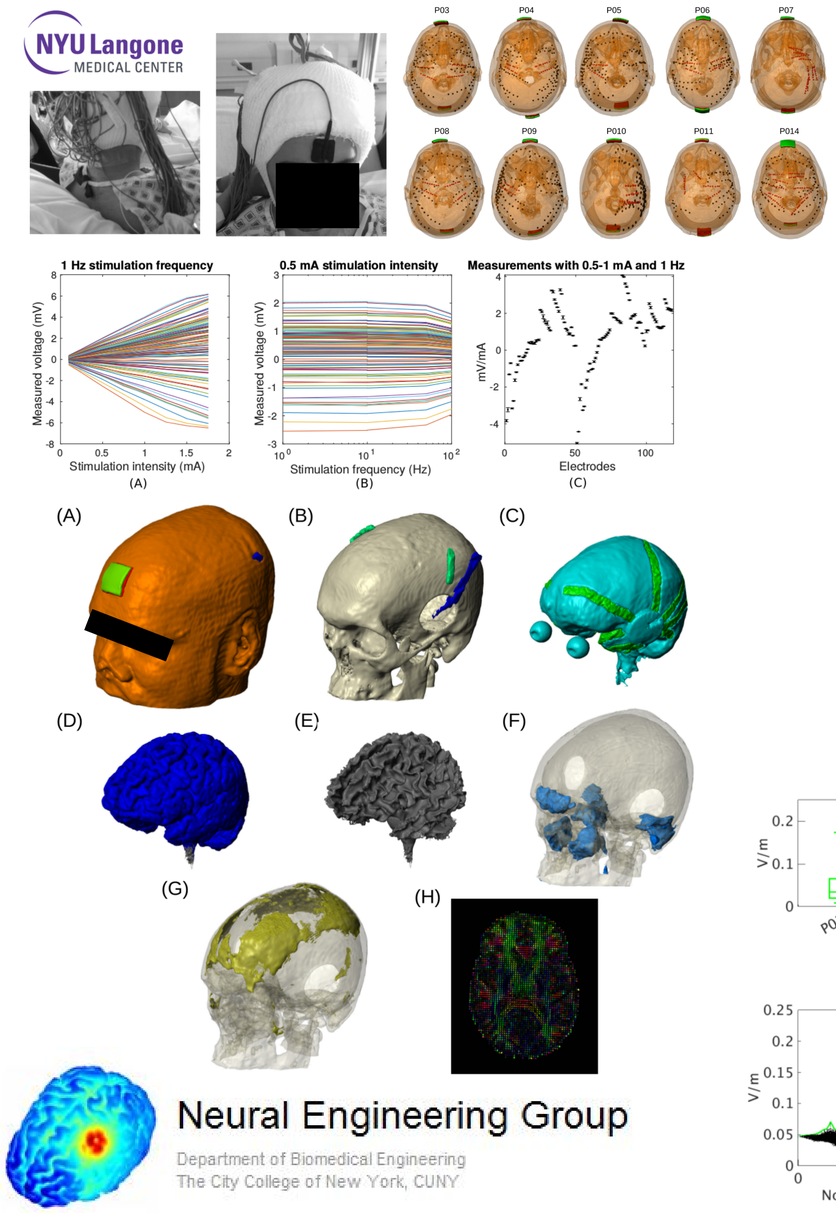
Abstract

Transcranial electric stimulation aims to stimulate the brain by applying weak electrical currents at the scalp. However, the magnitude and spatial distribution of electric fields in the human brain are unknown.

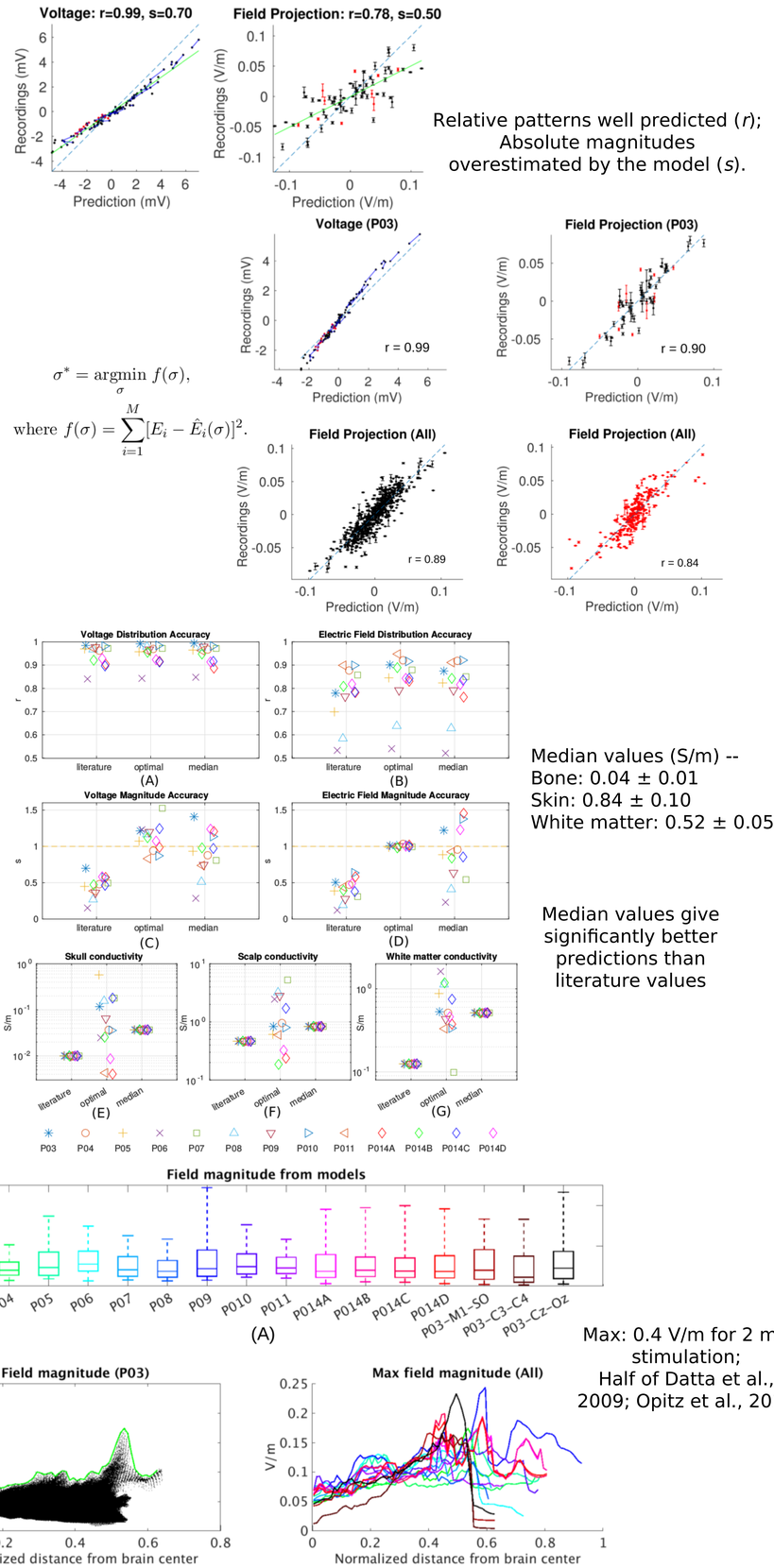
We measured electric potentials intracranially in ten epilepsy patients and estimate electric fields across the entire brain by leveraging calibrated current-flow models. When stimulating at 2 mA, cortical electric fields reach 0.4 V/m, the lower limit of effectiveness in animal studies. When individual whole-head anatomy is considered, the predicted electric field magnitudes correlate with the recorded values in cortical (r = 0.89) and depth (r = 0.84) electrodes. Accurate models require adjustment of tissue conductivity values reported in the literature, but accuracy is not improved when incorporating white matter anisotropy or different skull compartments.

This is the first study to validate and calibrate current-flow models with *in vivo* intracranial recordings in humans, providing a solid foundation to target stimulation and interpret clinical trials.

Method



Results



$$\sigma^* = \underset{\sigma}{\operatorname{argmin}}\ f(\sigma),$$

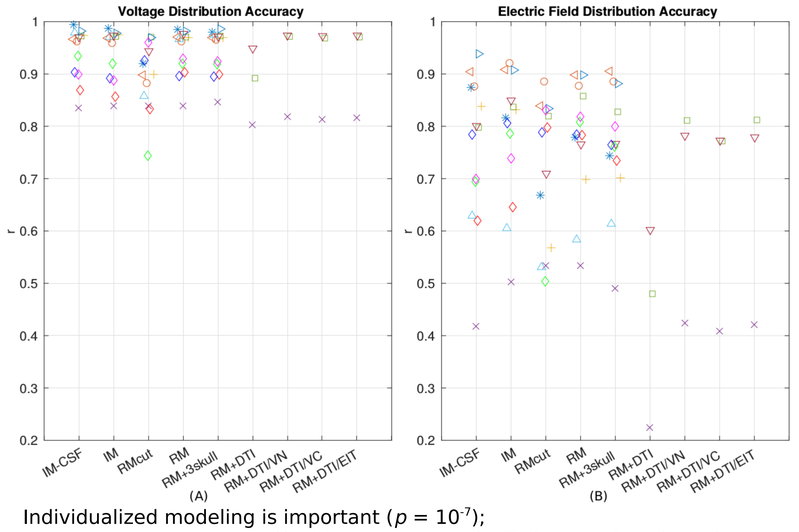
$$\text{where } f(\sigma) = \sum_{i=1}^{M} [E_i - \hat{E}_i(\sigma)]^2.$$

Relative patterns well predicted (r); Absolute magnitudes overestimated by the model (s).

Median values (S/m) --
Bone: 0.04 ± 0.01
Skin: 0.84 ± 0.10
White matter: 0.52 ± 0.05

Median values give significantly better predictions than literature values

Max: 0.4 V/m for 2 mA stimulation;
Half of Datta et al., 2009; Opitz et al., 2016



Individualized modeling is important ($p = 10^{-7}$);
A whole-head model is better than a model cut off at nose (RMcut vs. RM, p = 0.03);
Model without CSF gives worse prediction on electric field magnitudes (IM vs. IM-CSF, $p = 10^{-7}$);
Modeling skull compartments gives worse prediction on electric field distribution (RM vs. RM+3skull, p = 0.04);
Incorporating DTI does not seem to help.

Discussion

First attempt to validate tES models. The model predicts the relative distribution patterns of electric field in the brain well with r = 0.89, meaning models can be used to select the optimal electrode configuration to target interested brain region.

Electric field recorded is up to 0.4 V/m under 2 mA stimulation, half as reported in Opitz et al., 2016, as they placed the stimulation electrodes close to the craniotomy sites.

A model truncated at the bottom of the skull significantly worsens the predictions. Individual anatomy including the CSF is important, but white matter anisotropy and different conductivities of bone compartments do not significantly improve the prediction performance. But this conclusion needs further evaluation, as the current experimental setup only follows clinical consideration, i.e., recording electrodes do not necessarily capture the hot spot of electric field, nor the electric field magnitude. They need to be placed in white matter and spongy bone to test this further.

The best-fit values are not necessarily the actual physical tissue conductivities. They depend on the location of tES electrodes, segmentation errors and model complexity.

Future modeling endeavors can be evaluated by this dataset (recordings, MRIs) publicly available at http://dx.doi.org/10.6080/K0XW4GQ1

Reference:

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